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Field evaluation of Salomon Alpine ski clothing:

Three multilayer clothing ensembles

S.J. Davies
M B. Ducharme

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External Client Report
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Defence and Civil Institute of Environmental Medicine

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This study, approved by the Defence and Civil Institute of Environmental Medicine (DCIEM) Human Research Ethics Committee, was conducted in conformity with the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

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Abstract

DCIEM field-tested three prototype ski clothing ensembles for thermal and vapour transfer characteristics. Each ensemble differed in their combinations of insulation and shell fabrics, which would affect their capacity to retain heat and transfer water vapour to the environment. Three male subjects were used to test three conditions. Each condition required a chairlift ascent before skiing in sequence each of 14 pre-set, intermediate to expert descents at a western Canadian ski resort. Subjects experienced 268.0 minutes (+/-7.0 minutes) exposure of which 85.3 minutes (+/-4.7 minutes) were active skiing. Subjects' activity levels averaged 3.7 times greater than rest. No ensemble provided effective comfort since all toe temperatures were 3 degrees below 15°C. Lower body garments provided less protection than the upper body. Subjects perceived wind permeability as an important comfort factor. During rest, garment compression and increased conductivity was observed which caused subject's legs and back to lose a larger amount of heat to the previously weather-exposed chairlift seat. When activity changed from rest to skiing the areas that experienced greatest heat flux and skin temperature changes were hamstring, abdomen and chest. Skiing activity and its resultant air flow increased heat flux for subjects anterior torso and legs. Sweat accumulation was never a concern in this trial. The ensemble with windproof upper body insulation and outer shells maintained more constant and desirable skin temperature, heat flux, thermal comfort, perceived exertion, clothing insulation and system insulation without noticeable water vapour accumulation.

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Résumé

L'IMED a soumis trois ensembles prototypes de vêtements de ski à des essais pratiques visant à déterminer les caractéristiques de transfert de la chaleur et de la vapeur. Chaque ensemble différait dans sa combinaison de tissu isolant et de tissu extérieur qui avait une incidence sur la capacité de conserver la chaleur et de transférer la vapeur d'eau à l'air libre. Trois sujets de sexe masculin ont servi aux essais sous trois conditions différentes. Chaque condition exigeait une montée en télésiège suivie d'une période de ski en séquence de 14 descentes prédéterminées, niveau intermédiaire à expert, dans une station de ski de l'Ouest canadien. Les sujets ont été soumis à 268,0 minutes (+/- 7 minutes) d'exposition dont 85,3 minutes (+/-4,7 minutes) étaient accordées au ski actif. Les degrés d'activité des sujets étaient en moyenne 3,7 fois plus élevés que les autres. Aucun ensemble n'a assuré un confort entier puisque les températures des orteils étaient de 3 degrés sous 15 °C. Les vêtements du bas du corps fournissaient moins de protection que ceux du haut. Les sujets ont observé que la perméabilité au vent était un facteur important de confort. Pendant les périodes de repos, les sujets ont senti une compression des vêtements et une augmentation de la conductivité causant une perte plus importante de chaleur aux jambes et au dos des sujets auparavant exposés à la température du télésiège. Lorsque l'activité de ski reprenait après une période de repos, les tendons du jarret, l'abdomen et la poitrine étaient les parties du corps où l'on observait le flux de chaleur et les écarts de température les plus élevés. L'activité de ski et le flux d'air associé ont entraîné une augmentation du flux thermique au niveau du torse et des jambes antérieurs. L'accumulation de vapeur d'eau (sueur) n'a jamais été une préoccupation dans cet essai. L'ensemble comprenant la couche isolante et le tissu extérieur résistant au vent à la partie supérieure du corps maintenait une température de la peau, un flux thermique et un confort thermique plus constants et désirables. Cet ensemble permettait également de percevoir l'effort fourni tout en assurant une bonne isolation des vêtements et du système sans accumulation perceptible de vapeur d'eau.

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Executive summary

Salomon is expanding their business and expertise with a new line of technical clothing products. DCIEM was approached to test three ski clothing prototype ensembles for thermal and water vapour transfer characteristics. The main objective was to investigate which prototype ensemble provided the best thermal comfort and protection during Alpine skiing: Ensemble one (ONE) had an abdomen-pocketed Schoeller WB-400 outer top, a nylon-lined two-ply Gore Tex outer bottom, a three-dimensional mesh insulation top, a long-sleeved X-Static undershirt and a pair of full-length X-Static underpants. Ensemble two (TWO) had an internally hooded, chest-pocketed, internal snow-belted Schoeller WB-400 outer top, a Schoeller WB-400 outer bottom, a traditional zippered, oversized fleece insulation top, a long-sleeved X-Static undershirt and a pair of full-length X-Static underpants. Ensemble three (THREE) had a hooded, internal snow-belted, three-ply Gore Tex XCR outer top, a three-ply Gore Tex XCR outer bottom, a zippered nylon/polyester-lined Primaloft insulation top, a long-sleeved X-Static undershirt and a pair of full-length Outlast underpants. ONE has an air permeable top and a wind resistant bottom. TWO has an air permeable top and bottom. THREE has a wind resistant top and bottom with multilayer torso insulation. Three male subjects were used to test the three experimental conditions at an average ambient temperature of 1°C. Each condition required a chairlift ascent before skiing in repeated sequence each of 14 pre-set, intermediate to expert descents. Subjects experienced 268 minutes (+/-7 minutes) exposure of which 85.3 minutes (+/-4.7 minutes) were active skiing. Tests were performed on six consecutive days in March 2001 at a western Canadian ski resort. No ensemble provided effective comfort since all toe temperatures were 3 degrees below 15°C. Subjects complained of wind permeability effects when ONE or TWO were worn. Clothing ensemble THREE was the most thermally comfortable for rest and skiing under the ambient condition tested. The windproof layer was responsible for the preference toward clothing ensemble THREE. Insulation for the lower body needs to be increased to ensure thermal comfort. Sweat accumulation was never a concern in this trial as each ensemble was under insulated. If an ensemble had to be selected as is for comfort and protection in the condition tested, THREE would be favourable.

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Sommaire

L'entreprise Salomon est en train d'accroître son champ d'activité commerciale et son expertise avec une nouvelle gamme de vêtements techniques. L'IMED a été approché afin de mettre à l'essai trois prototypes de vêtements de ski visant à déterminer les caractéristiques de transfert de la vapeur d'eau et de la chaleur. L'objectif principal était d'établir après enquête quel prototype fournissait le meilleur confort thermique et la meilleure protection lors d'excursions de ski alpin. L'ensemble un (UN) comprend un haut extérieur à pochette sur l'abdomen Schoeller WB-400, une partie inférieure en Gore-Tex deux plis, à doublure de nylon, un haut isolant à mailles tridimensionnelles, un gilet de corps X-Static à manches longues et un sous-vêtement inférieur pleine longeur X-Static. L'ensemble deux (DEUX) est constitué d'un haut extérieur Schoeller WB-400 à capuche intérieure, à pochette sur la poitrine et ceinturé à l'intérieur contre la neige, un bas extérieur Schoeller WB-400, un haut isolant molletonné classique, très ample, à fermeture à glissière, un sous-vêtement supérieur X-Static à manches longues et un sous-vêtement inférieur pleine longueur X-Static. L'ensemble trois (TROIS) comprend un haut extérieur en Gore Tex XCR à trois plis, à capuchon, ceinturé à l'intérieur contre la neige, un bas extérieur Gore Tex XCR à trois plis, un haut isolant à fermeture à glissière et à doublure en nylon/polyester Primaloft, un gilet de corps à manches longues X-Satic et un sous-vêtement inférieur pleine longueur Outlast. L'ensemble UN comprend un haut perméable à l'air et un bas résistant au vent. L'ensemble DEUX comprend un haut et un bas perméables à l'air. L'ensemble TROIS comprend un haut et un bas résistant au vent et un isolant multicouches pour le torse. Trois sujets de sexe masculin ont été utilisés afin de mettre à l'essai les trois conditions expérimentales à une température ambiante moyenne de 1 °C. Chaque condition exigeait une montée en télésiège avant une période de ski en séquence répétée de 14 descentes prédéterminées, niveau intermédiaire à expert. Les sujets ont été soumis à 268 minutes (+/- 7 minutes) d'exposition dont 85,3 minutes (+/- 4,7 minutes) de ski actif. Les essais ont été exécutés pendant six jours consécutifs en mars 2001 dans une station de ski de l'Ouest canadien. Aucun ensemble n'a fourni un confort entier, car les températures des orteils étaient de 3 degrés sous 15 °C. Les sujets se sont plaints des effets causés par la perméabilité au vent lorsque les ensembles UN et DEUX étaient portés. L'ensemble TROIS présentait le confort thermique le plus élevé au repos et en période de ski sous les conditions ambiantes d'essai. La couche résistant au vent était responsable de la préférence accordée au prototype TROIS. L'isolation du bas du corps doit être augmentée afin d'assurer un confort thermique adéquat. L'accumulation de vapeur d'eau n'a jamais été une préoccupation dans le présent essai, chaque ensemble étant sous-isolé. Si un ensemble doit être sélectionné dans sa condition actuelle, l'ensemble TROIS serait le plus avantageux au point de vue confort et protection sous les conditions expérimentales d'essai.

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1. Introduction

Salomon expanded its scope of expertise by development of technical clothing for a variety of outdoor sports including alpine skiing. The company approached DCIEM to test three prototype alpine ski clothing ensembles for thermal and vapour transfer characteristics. The main differences between ensembles related to the type of upper body insulation and the outer shell's air permeability. One ensemble had mesh foam insulation top, stretch wind permeable jacket and breathable windproof pants, the second ensemble had fleece top and stretch wind permeable jacket and pants while the third ensemble had multilayer lofted insulation top and breathable windproof jacket and pants. All ensembles were developed by Salomon to provide comparable thermal insulation using several non-Salomon garments.

The main objective of the comparative study was to test the thermal and water vapour transfer characteristics of the clothing prototypes during alpine skiing in the field, and to evaluate their effect on the thermal responses and thermal comfort.

2. Methods

2.1 Subjects

Three male subjects participated in the present experiment. Their physical characteristics are outlined in the table below. Subjects were asked to avoid alcohol, caffeine and intense exercise twelve hours before each experimental session. Subjects were informed of the study procedures and each signed a volunteer consent form before participation. The protocol (L-291) was approved by the DCIEM Human Ethics Committee.

Table 1: Subject characteristics

Subject	Age (yr)	Height (cm)	Mass (kg)	Surface Area (m^2)	VO_2max (l/min)	VO_2max (ml/kg/min)	Body fat (%)
1	37	184	78 0	2 00	2 9	36 9	13 8
2	30	184	90 7	2 14	3 6	39 6	17 7
3	24	187	68 0	1 92	2 8	41 8	13 5

2.2 Preliminary test

Each subject was medically screened by a physician before his participation was accepted. Each subject performed a sub-maximal aerobic power test (VO_2max test) on a stairway that involved six increases in cadence up and down two stairs from floor level. The test was used to extrapolate each subjects skiing intensity (VO_2 consumption) from their recorded heart rates. Percent body fat was estimated from five skin-fold measurement (triceps, subscapular, suprailiac, abdominal and quadriceps) using the Plyley, Shephard and Forsyth formula (1). Body surface area was estimated with the Dubois and Dubois formula (2).

2.3 Procedures

Each experiment was a half-day of alpine skiing. Each test required seven hours to weigh individual items, dress subjects, ski, undress subjects and weigh individual items. All sessions began in the morning after an in-house breakfast and within two hours of the same time each day beginning March 11th 2001 for six consecutive days. Each day involved a different clothing test condition. Subject 1 wore each clothing ensemble twice over six days while Subjects 2 and 3 wore each ensemble once over

three consecutive days. Salomon provided all garments except for socks, boots, gloves, hats and goggles.

Each garment's mass was measured both before and after daily use. After skiing and undressing each garment was rapidly placed inside a plastic bag to prevent evaporative moisture / mass loss before it was measured. Each garment was cleaned as necessary then hanged to dry. Both subjects came to the scale area where their individual nude mass was measured while standing on a floor scale behind a privacy curtain. Subjects dressed in their underwear before meeting at the dressing area. Each subject's skin was cleaned with Reddi-Prep Alcohol Swabs (Ingram & Bell Medical, Don Mills, ON) and SkinPrep Protective Dressing Wipes (Smith & Nephew, Largo, FL) over the heat flux transducer sites. The same experimenter dressed the same subjects to standardise skin sensor placement. Using Transpore Surgical Tape (3M Canada, London, ON) a heat flux transducer was taped to each of chest, abdomen, upper back, lower back, arm, anterior thigh and posterior thigh muscle groups. A Polar Vantage NV heart rate chest strap transmitter was placed around each subject's chest while the wristwatch recorder was placed inside the skiers pocket. A humidity sensor was taped over the anterior thigh, lower back and upper back regions. A thermistor (Yellow Springs Instrument, Yellow Springs, OH) was taped beside the nail of the left large toe; subjects wore their own socks and underwear before dressing in their own X-Static long underwear. A humidity sensor was taped to the X-Static underwear adjacent to each of the underlying skin humidity sensors. Outer ski pant bottoms were belted with the data loggers attached to nylon webbing. All heat flux transducers and humidity sensors attached to one of five data loggers worn on the belt. The insulation top was donned over the data logger belt and before the outer jacket. Two external data loggers were placed in outer pockets once connected to the pants' and jackets' external thermistors. A dressed mass was measured before hats, gloves, goggles and neck warmers were worn.

Subjects walked down two floors, put on their ski boots and walked outdoors with their skis and poles through 50m of forest and over 250m of parking lot to the ski lift. Subjects skied with one investigator from this time through the ski activity until they walked back to accommodations for mass measurements and undressing. A card displaying the Perceived Exertion and Thermal Comfort scales was attached to each subject's jacket. After a descent, each subject rated both scales; before descent, only Thermal Comfort was rated. During experimental sessions, subjects were permitted to adjust clothing vents and collars but never did.

The ambient conditions were not controlled as all experimental sessions were performed outdoors. Average ambient air temperature for each suit was measured 15 centimetres above each subject's shoulder. Precipitation never fell. Skies were mostly cloudy. Fourteen pre-set intermediate to expert descents were skied in the same order each test day according to possible lift closures and degraded snow conditions predicted for our week; terrain was month-old snow in steep moguls, trees and groomed runs with hard packed snow. Brief rests were taken on particular descents when one of the three skiers was out of view. An experimenter skied with the two subjects at all times unless terrain or abnormal lunch arrangements required.

The experimenter wore a backpack containing two FM radios - one to contact mountain rescue and another to contact a second experimenter; a cellular telephone, a first aid kit, two urine bottles and two Gatorade-filled (Quaker Oats Company of Canada Ltd, Peterborough, ON) bottles were carried. A lunch for each subject was delivered on the mountain by the second experimenter. The lunch was a submarine sandwich and either a chocolate bar or a bag of potato chips. Lunch was eaten during the next chairlift ascent; great care was taken to prevent dropped food as all items were weighed together. Dropped food would impact the calculation of sweat loss. Subjects were free to drink from their respective Gatorade-filled bottle whenever desired; subjects could also plan a stop for urine collection during several suitable descents. The masses of each drink, food and urine volume generated or consumed were measured.

A specifically designed switchbox was worn by Subject 1 and the skiing experimenter, as both skiers would be active for each of the six consecutive experimental days. Each switchbox was connected to a data logger. When switched upward a red light on the switchbox was lit and a known voltage passed to the data logger indicating rest rather than skiing activity. The voltage was recorded each minute alongside the external suit data and was later used to synchronize both subjects' rest and ski activities for the same experimental session.

2.4 Clothing

Each ensemble differed in garment and fabric combinations to impact insulation, water vapour transport and air permeability. Ensemble one (ONE) had an abdomen-pocketed Schoeller WB-400 outer top, a nylon-lined two-ply Gore Tex outer bottom, a three-dimensional mesh foam insulation top, a long-sleeved X-Static undershirt and a pair of full-length X-Static underpants. Ensemble two (TWO) had an internally hooded, chest-pocketed, internal snow-belted Schoeller WB-400 outer top, a Schoeller WB-400 outer bottom, a traditional zippered, oversized fleece insulation top, a long-sleeved X-Static undershirt and a pair of full-length X-Static underpants. Ensemble three (THREE) had a hooded, internal snow-belted, three-ply Gore Tex XCR outer top, a three-ply Gore Tex XCR outer bottom, a zippered nylon/polyester-lined Primaloft insulation top, a long-sleeved X-Static undershirt and a pair of full-length Outlast underpants. ONE had an air permeable top and a wind resistant bottom. TWO had an air permeable top and bottom. THREE had a wind resistant top and bottom with wind resistant insulated top.

2.5 Measured parameters

2.5.1 Heat flow and skin temperature

Heat flow and skin temperature were measured from seven locations (see Table 2). Heat flow discs (Old Saybrook, Connecticut, USA) were fixed to

the skin with Transpore Surgical Tape (3M Canada, London, ON). A temperature probe was taped beside the left foot's large toenail. ACR Smart Readers (ACR Systems, Surrey, BC) were used to record temperature and heat flux values each minute.

Mean body heat loss and mean body skin temperature were calculated based on a modified Hardy and Dubois weighting factor system average of seven sites (3).

Table 2: Mean skin temperature and body heat flow weighting coefficients

Sensor location	*Weighting factor*
Chest	0.088
Abdomen	0.088
Upper back	0.088
Lower back	0.088
Upper arm	0.140
Anterior thigh	0.095
Posterior thigh	0.095

2.5.2 External suit temperature

External suit temperature thermistors (YSI Inc, Yellow Springs, OH) were placed over the underlying location used for skin heat flow and skin temperature. Exterior temperature probes were fixed on the clothing with Duct Tape (3M Canada, London, ON). ACR Smart Readers (ACR Systems, Surrey, BC) recorded external suit temperature values each minute.

2.5.3 Heart rate

Heart rate was measured each 20 seconds using a Polar Vantage NV heart rate monitor (Polar Electro Inc, Port Washington, NY) with the transmitter strapped around the chest and the wristwatch receiver and memory storage placed inside a clothing pocket. Suspenders kept the chest strap in place during experimental sessions.

2.5.4 Metabolic rate

Oxygen uptake was assessed during a five-stage stair climbing maximal exercise assessment. Subjects breathed through a medium flow open pneumotach mouthpiece equipped with an expiratory gas tube that directed samples to an accompanying TEEM100 Metabolic Analysis System (Aerosport Inc, Ann Arbor, MI). Expired volume was calculated by a comparison of pressure differences on the internal and the external sides of the mouthpiece orifice plate. TEEM100 gas sensors were calibrated with calibrating gas (Scotty Mini-Mix, 16%O2, 4%CO2; Scott Specialty Gases, Plumsteadville, PA). Data were recorded and printed by the TEEM100 directly after each exercise session. When a steady state heart rate was reached during each of the five exercise stages, the corresponding stabilized oxygen consumption was recorded. Heart rate for each exercise stage was plotted against oxygen consumption to derive metabolic cost for each subject at each heart rate. Heart rates recorded during each experimental session then had an extrapolated percent of maximal oxygen consumption.

2.5.5 Heat balance

Radiative, convective and conductive heat flows, designated as R + C + K, were measured using 2x25mm diameter heat flux transducers with embedded thermistors (Concept Engineering, Old Saybrook, CT). The mean body heat flux (W/m^2) for each subject was multiplied by their surface area (m^2) to determine the mean body heat flow in watts (W).

Evaporative heat loss from the skin (E) was estimated from a model developed by Cain and McLellan (4) that used vapour pressure readings obtained with three pairs of humidity sensors positioned at a theoretical distance of 5 and 15mm above the skin surface. Each 10mm diameter plastic housing was taped to the skin with Transpore Surgical Tape (3M Canada, London, ON) leaving the internal sensor 5mm from skin. If placed directly above the underlying skin humidity sensor, the clothing layer humidity sensor could be 15mm from skin surface not including the underlying fabric and tape thickness (<1mm). A temperature thermistor (Yellow Springs Instrument, Yellow Springs, OH) was attached to the exterior of each plastic housing. Humidity sensor pairs were placed each on the chest centre, the upper back centre and the anterior left front thigh. Skin water vapour pressure (VPs) was estimated from the inter-garment water vapour measurements and used in calculating E. The model was viewed as a one-dimensional water vapour flow through multiple layers of resistive garments.

2.5.6 Ratings of thermal comfort and perceived exertion

Thermal Comfort was rated by each subject both before and after each descent; the McGinnis 13 point Thermal Comfort Scale (see Annex) was used. Perceived Exertion was rated by each subject after each descent; the

Borg 15 point Perceived Exertion Scale (see Annex) was used. A card displaying both scales was attached to each subject's jacket.

2.5.7 Sweat produced and sweat evaporated

Sweat produced and sweat evaporated was calculated as the difference between corrected pre-trial and post-trial nude and dressed weights after such values were corrected for fluid and food intake, urine production and metabolic weight loss (5). Individual garment masses were measured pre and post activity; any post-trial differences were calculated as mean sweat produced in garments and mean percent of produced sweat that remained in clothing.

2.5.8 Clothing and system insulation

Clothing insulation (Cclo) was calculated with this formula:

Cclo = ((weighted skin temp – weighted suit temp) / weighted heat flux) / 0.155

External suit temperature was measured with seven, 2x8mm thermistors fixed with Duct Tape (3M Canada Inc, London, ON) to the garments exterior corresponding to the skin-level heat flux sensors.

System insulation (Sclo) was calculated with this formula:

Sclo = ((weighted skin temp – ambient air temp) / weighted heat flux) / 0.155

Ambient air temperature was measured above the shoulder of each subject with a coiled thermistor wire as a cage keeping the sensor 15cm from the subject.

2.5.9 Garment water vapour permeability

Water vapour permeability was measured for each garment. Each garment's room temperature resistance to the diffusion of water vapour was determined with a device similar to van Best and Wittgen's (6). Garment panels were suspended above a 4mm airspace with the bottom of the airspace being a wet surface of Whatman Number 1 filter paper (Whatman International, Kent, UK) with dry air moving above the garment panel in a recirculated airspace. The relative humidity at the mean level of the sample was approximately 50%. The wet filter paper capillary forces hold water in a horizontal pipette situated just below the wet paper level. The wet surface evaporation rate is measured by noting the volume of water withdrawn from the pipette divided by time. Complete garments could be tested without cutting 8.3cm diameter fabric samples from each.

This apparatus measured the diffusion resistance of still air layers to tenths of a millimetre of equivalent standard still air (ESSA): 1mm ESSA = 5.4×10^{-6} m^2Pa s/kg. The dry air cell mass tends to compress the fibrous insulation of thick or multilayer garments such that a thick sample's lower surface intrudes into the air space above the wet filter paper. Thick or multilayer garment measurements could be underestimated by 4mm ESSA. Primaloft top SM01644, comprised of Primaloft insulation between nylon and polyester fabrics, would have been most vulnerable; the error could be a 19.2% underestimation of Ensemble THREE's total water vapour permeability.

2.6 Environmental conditions

Summit weather conditions were recorded daily at 08:00 and 14:00 hours. The ski resort management provided access to their automated data collection for temperature, relative humidity and wind velocity. Data supplied were single measurements. Fifteen centimetres above the shoulder of each subject was an external suit thermistor that was not taped to the jacket surface; this thermistor measured ambient air temperature.

2.7 Subject safety

Subject participation in any experimental session was terminated if an experimenter stopped an exposure or a subject requested withdrawal. No safety incidents arose.

2.8 Statistics

Statistical analysis was not performed as the requested number of subjects was inadequate. This was a limitation imposed by the client.

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3. Results

Values presented are averaged data originally collected every minute, except for heart rate data which were collected every 20 seconds. Subjects experienced average exposures of 268 minutes (+/- 7min); skiing required 85.3 minutes (31%) while rest required 182.7 minutes (69%). Subject One performed all conditions twice but the data was compiled as if a fourth subject participated. Standard deviations are expressed.

3.1 Heat flow

Body heat flow data are presented in Figures 1 to 8.

Heat fluxes were higher during skiing. Upper body heat fluxes were highest for ONE and TWO. Rest and ski heat fluxes differed least for THREE. Highest heat fluxes were from torso front and legs. Steadiest and lowest heat fluxes were from upper back, lower back and arm. Greatest rest-to-ski differences were from hamstring, abdomen and chest.

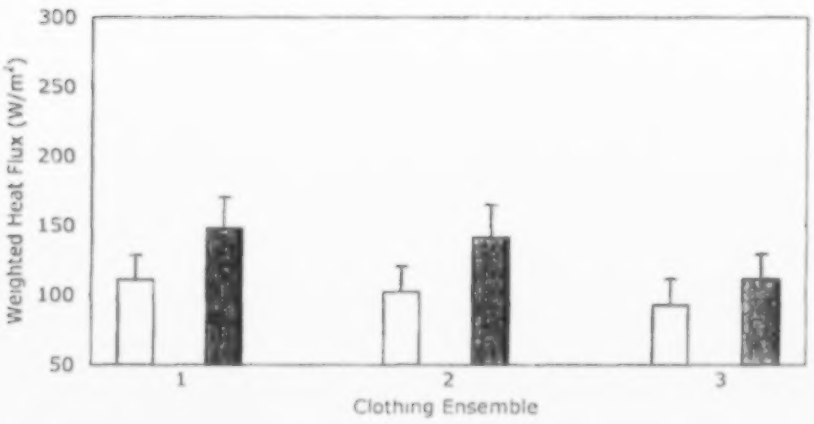

Figure 1: Weighted body heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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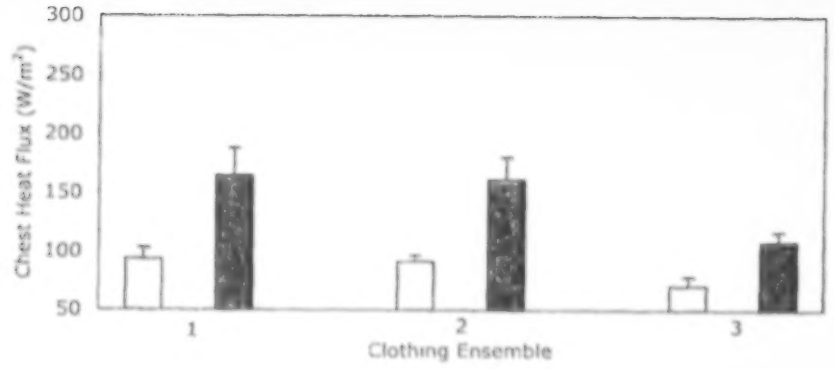

Figure 2. Mean chest heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

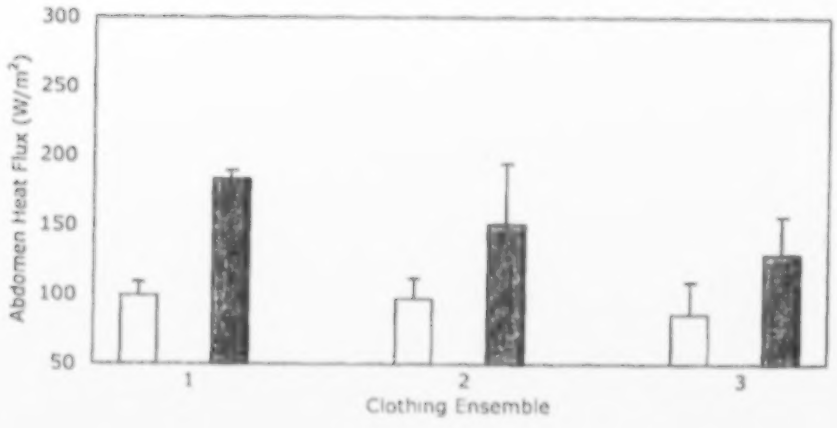

Figure 3: Mean abdomen heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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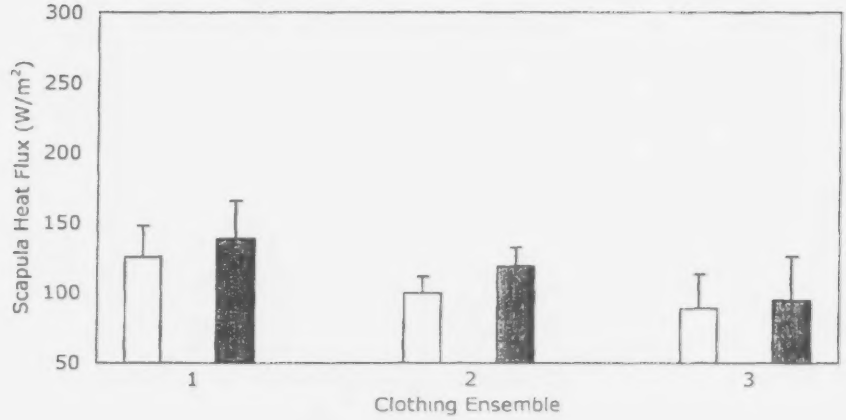

Figure 4: Mean upper back heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

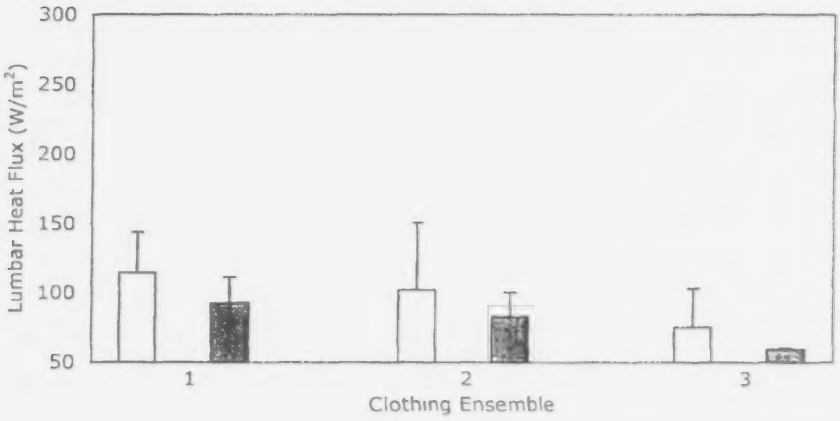

Figure 5: Mean lower back heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

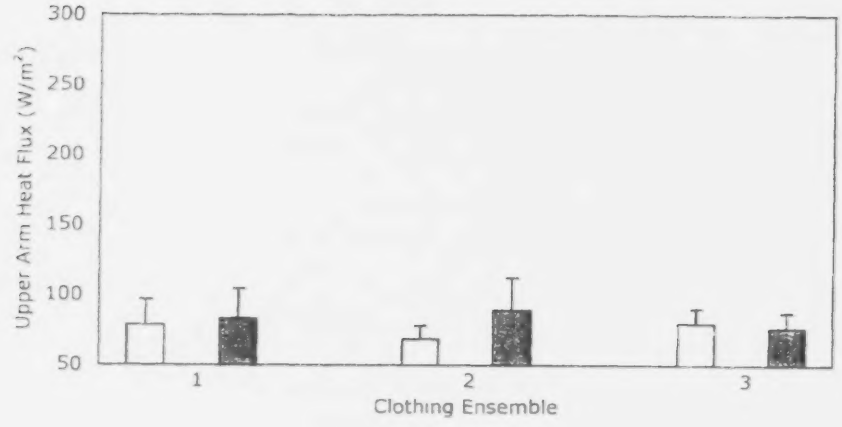

Figure 6: Mean arm heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

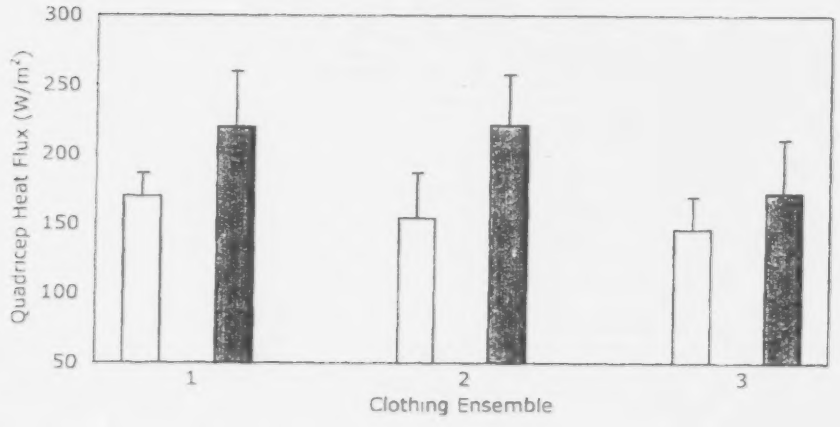

Figure 7: Mean front thigh heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

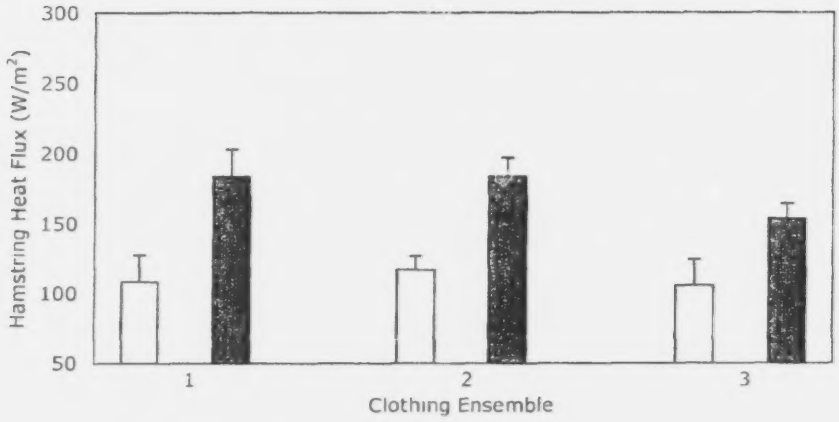

Figure 8: Mean hamstring heat flow of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

3.2 Skin temperature

Skin temperature data are presented in Figures 9 to 17.

Skin temperatures were higher during rest. Skin temperatures were highest, steadiest and differed least for THREE. Skin temperatures were lowest and most varied for ONE. Lowest leg temperatures were from TWO. Steadiest and highest temperatures were from posterior torso and arm. Greatest rest-to-ski differences were from front thigh. Toe temperatures were similar considering ambient temperatures.

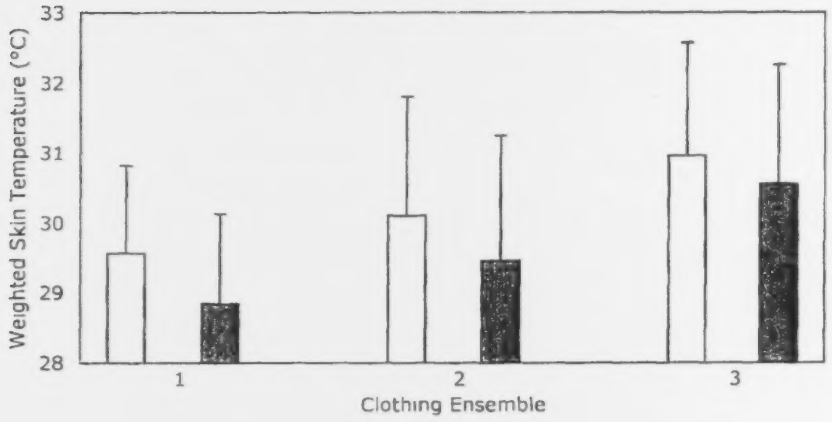

Figure 9: Weighted skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

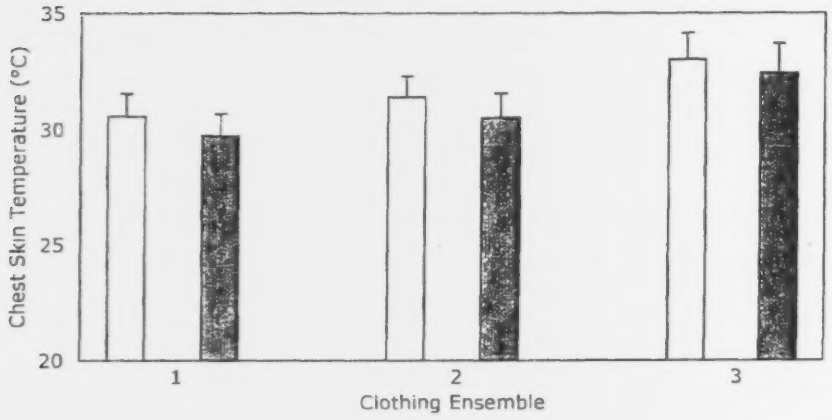

Figure 10: Mean chest skin temperature of all subjects during rest (white) and skiing (grey) while wearing one of three clothing ensembles.

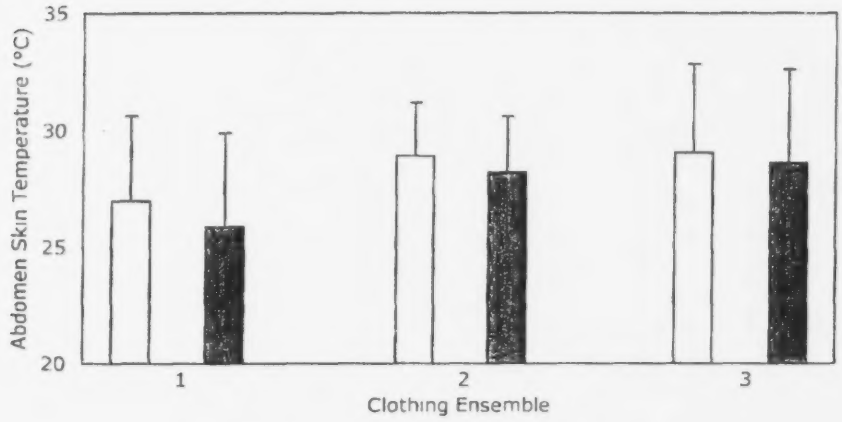

Figure 11: Mean abdomen skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

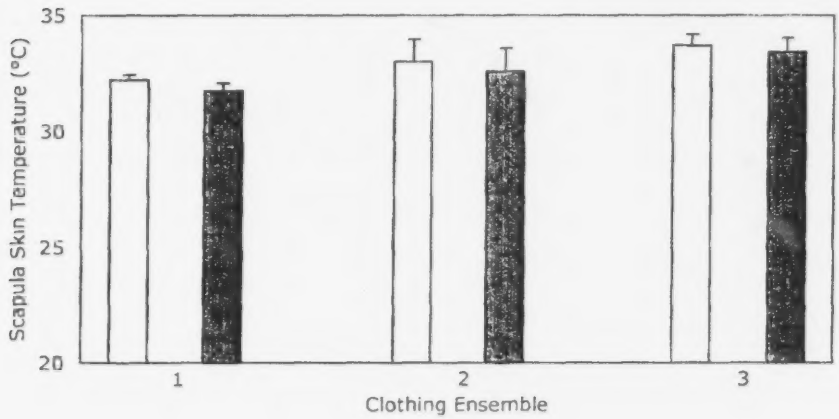

Figure 12: Mean upper back skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

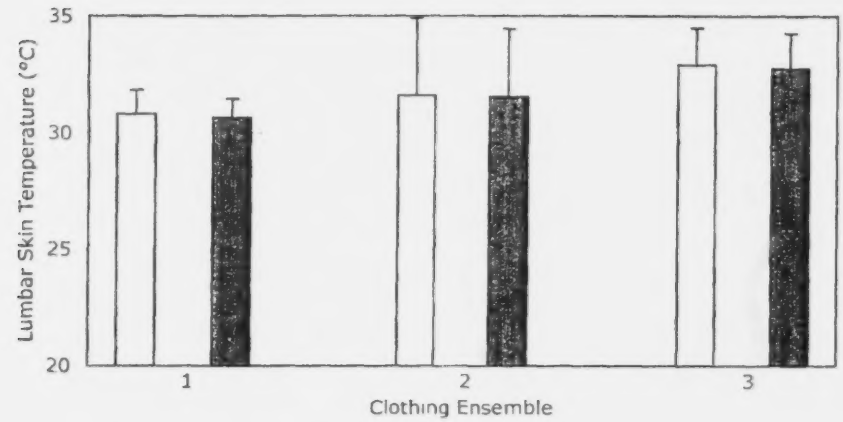

Figure 13: Mean lower back skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

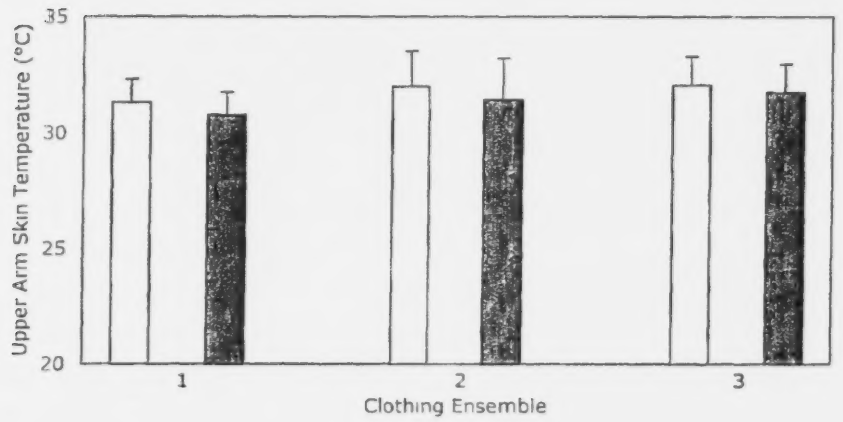

Figure 14: Mean arm skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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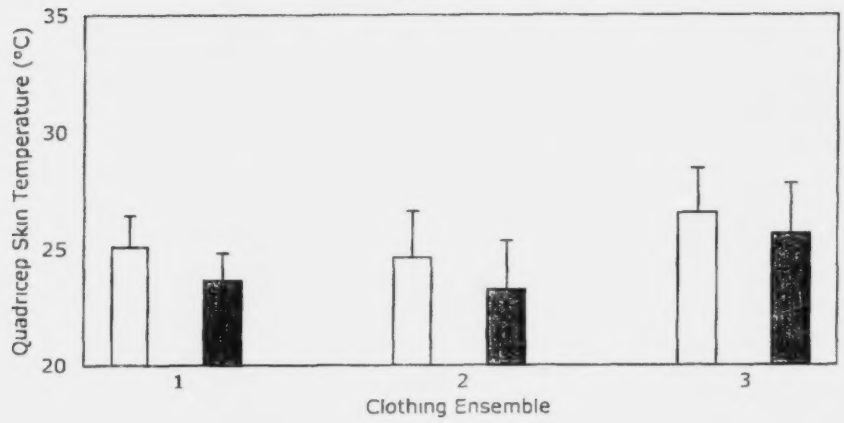

Figure 15: Mean front thigh skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

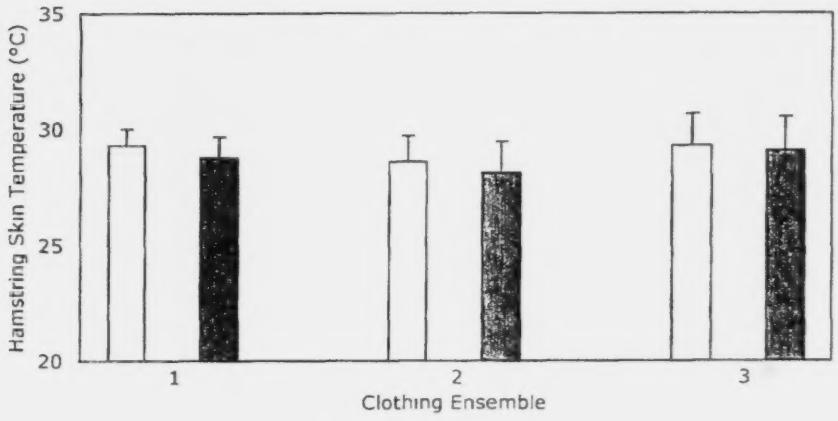

Figure 16: Mean rear thigh skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

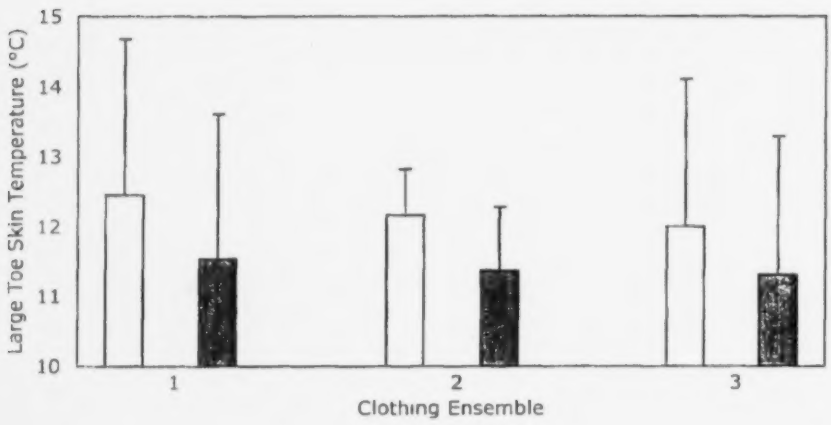

Figure 17: Mean toe skin temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

3.3 External suit temperature

External suit temperature data are presented in Figures 18 to 25.

External suit temperatures were higher during rest. Upper body suit temperatures were similar between ensembles. Highest temperatures were from legs and back. Steadiest and lowest temperatures were abdominal. Greatest rest-to-ski differences were from rear thigh.

Quadriceps external suit temperature sensor placement for THREE was proximal enough to be covered by the jacket or the arm during rest.

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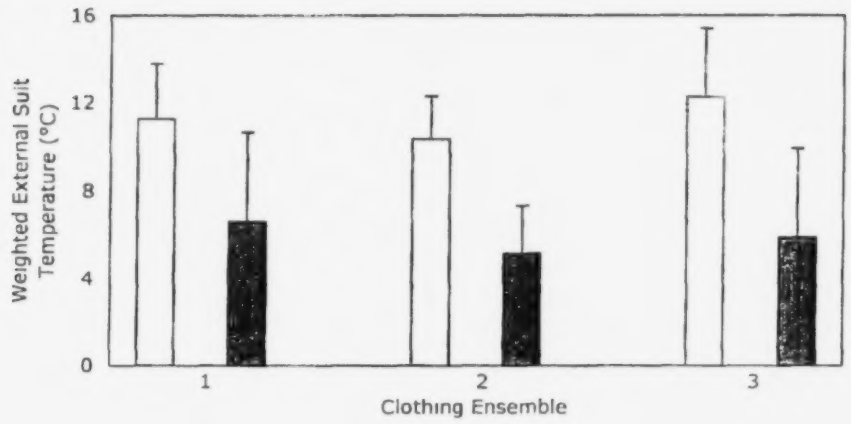

Figure 18: Mean external suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

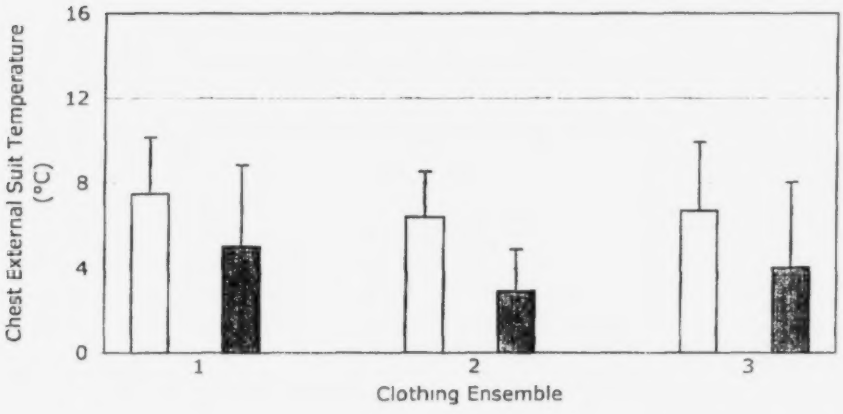

Figure 19: Mean external chest suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

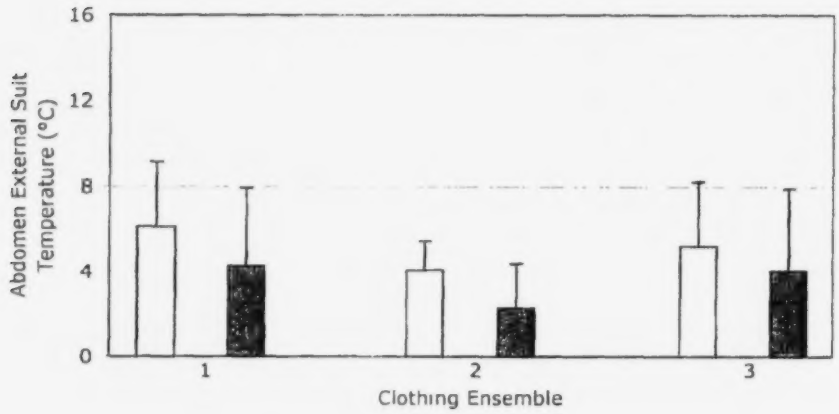

Figure 20: Mean external abdomen suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

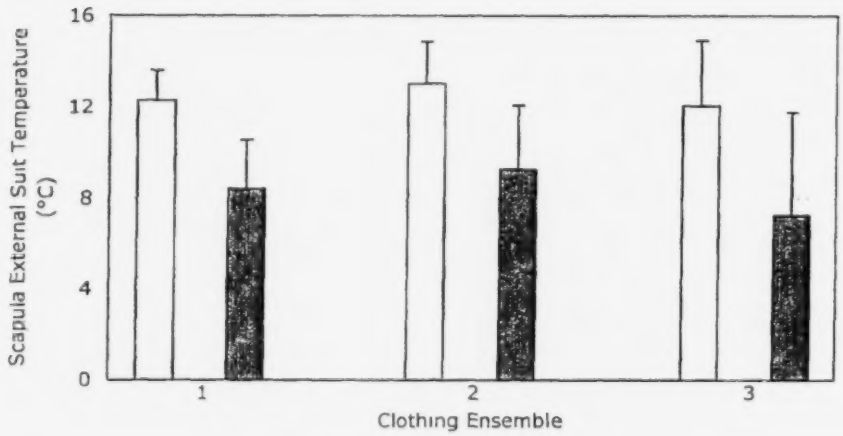

Figure 21: Mean external upper back temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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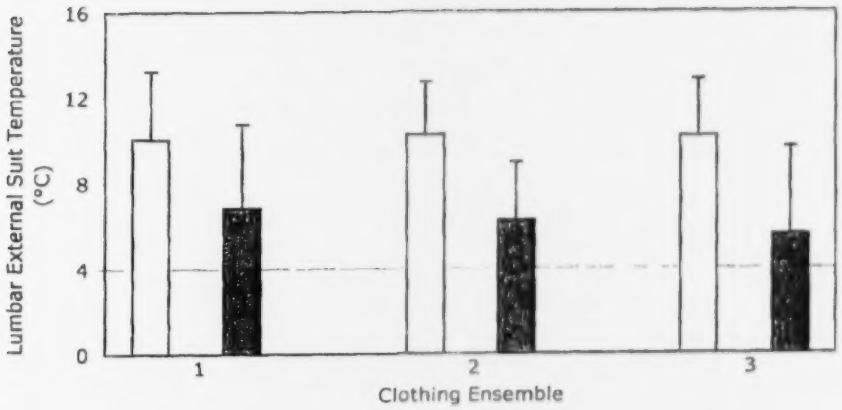

Figure 22: Mean external lower back suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

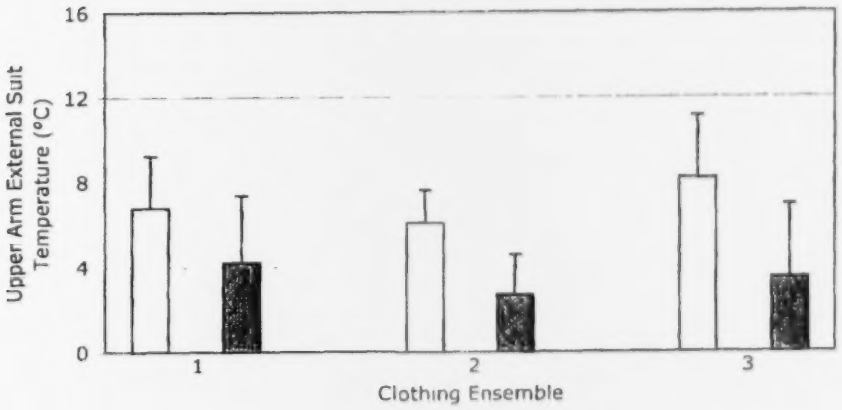

Figure 23: Mean external arm suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

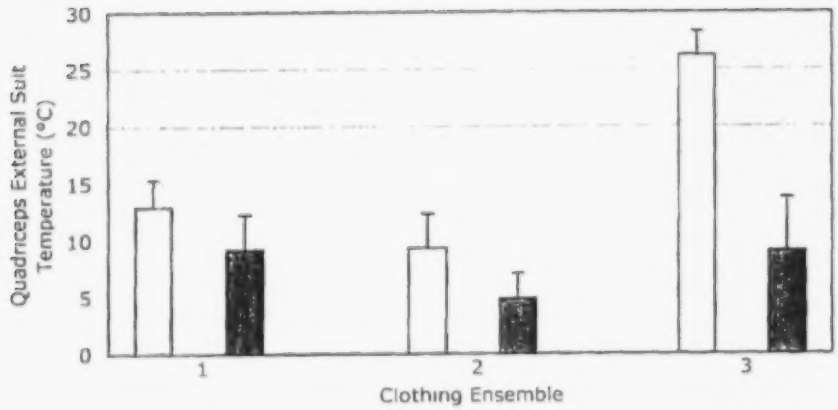

Figure 24: Mean external front thigh suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

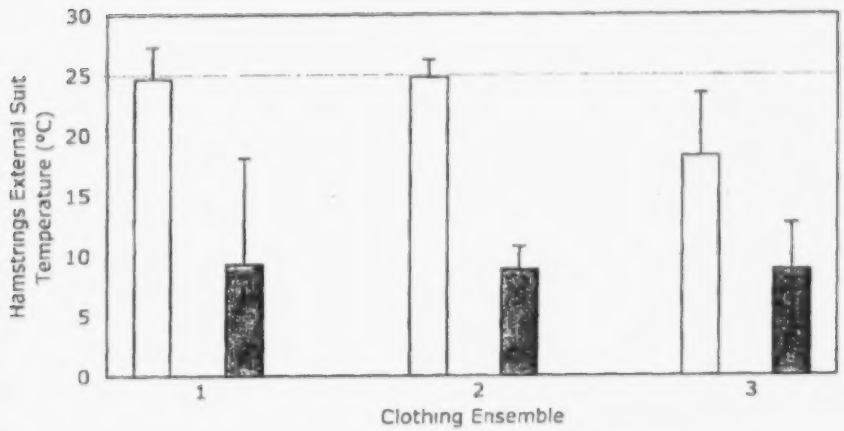

Figure 25: Mean external rear thigh suit temperature of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

3.4 Heart rate

Heart rate data are presented in Figures 26 to 29.

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Active heart rates were similar between ensembles. Resting heart rates were greatest with TWO. Subject TW, the most aerobically fit, lightest and youngest subject, had the greatest and most consistent rest and skiing heart rates. Subject TW may have skied more actively.

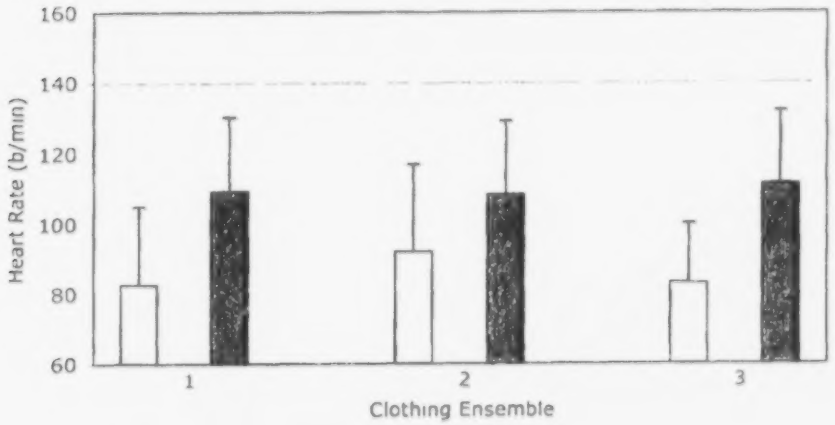

Figure 26. Mean heart rate of all subjects during rest (white) and skiing (grey) while wearing one of three clothing ensembles.

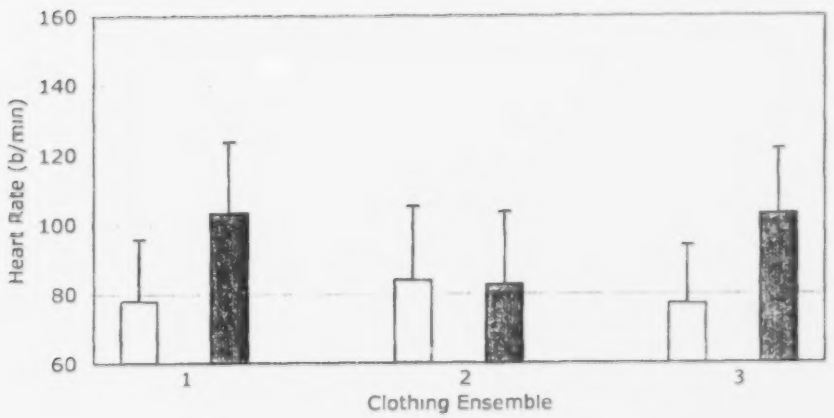

Figure 27. Mean heart rate of Subject 1 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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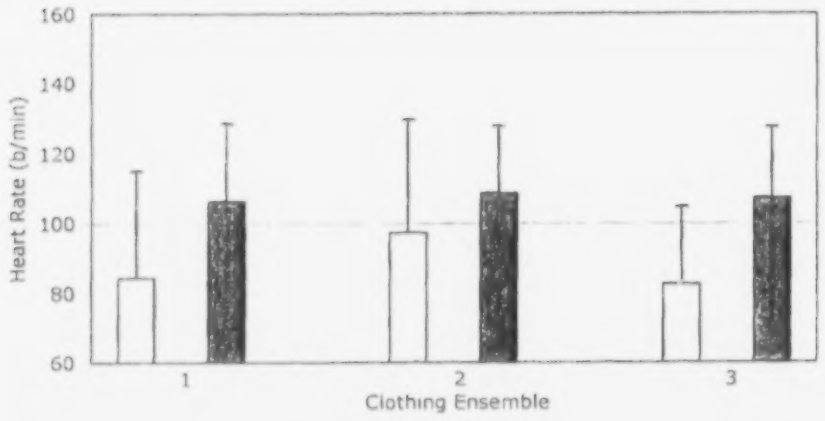

Figure 28: Mean heart rate of Subject 2 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

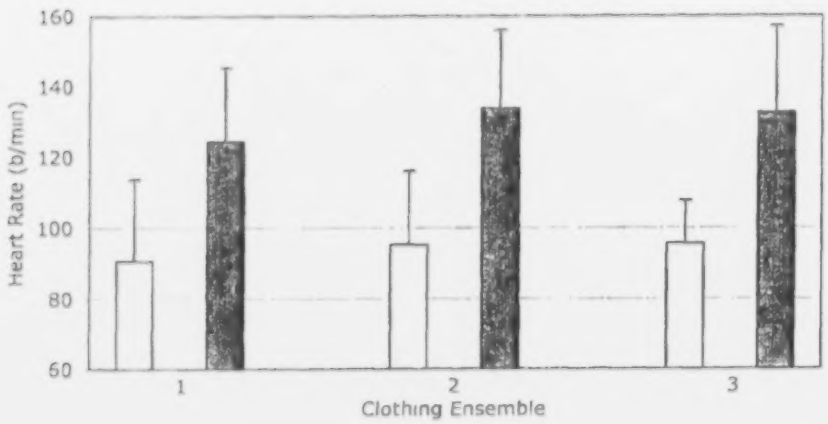

Figure 29: Mean heart rate of Subject 3 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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3.5 Metabolic rate

Metabolic rate data are presented in Figure 30.

Percent of maximal oxygen consumption was highest for TWO. Subjects' active metabolic rates averaged 3.73 times their average base resting metabolic rate of 4.47 ml/kg/min.

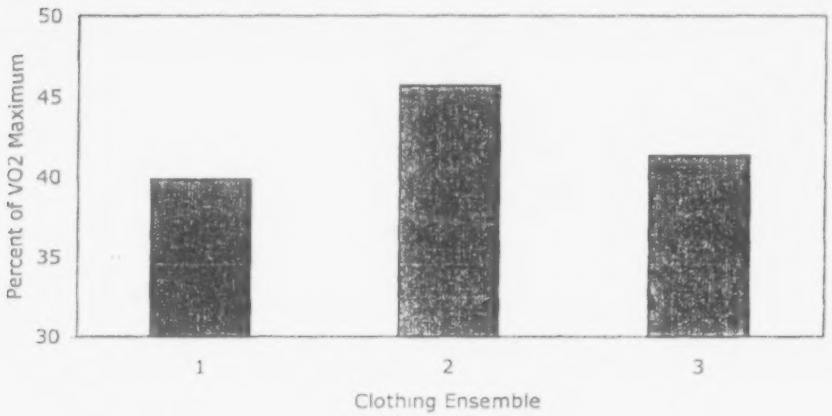

Figure 30: Average percent of maximal oxygen consumption for all subjects during rest and skiing while wearing one of three clothing ensembles.

3.6 Heat balance

Heat balance data are presented in Figure 31.

Evaporative heat loss was greatest for THREE.

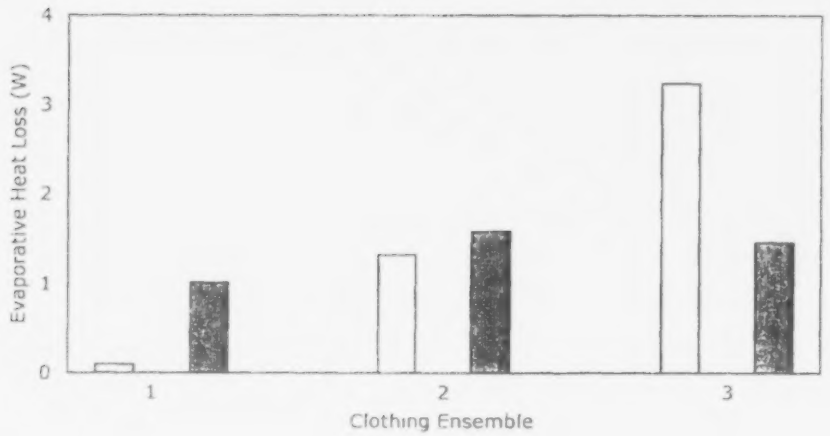

Figure 31: Average evaporative heat loss for all subjects for upper (white) and lower (grey) body while wearing one of three clothing ensembles.

3.7 Thermal comfort

Thermal comfort data are presented in Figures 32 to 35.

Thermal comfort ratings were higher after skiing. Thermal comfort ratings were highest for THREE. Rest and skiing thermal comfort ratings differed most for Subject JMR.

Subjects did not complain of heat stress but did complain of cold air circulation through their ensemble when ONE or TWO were worn.

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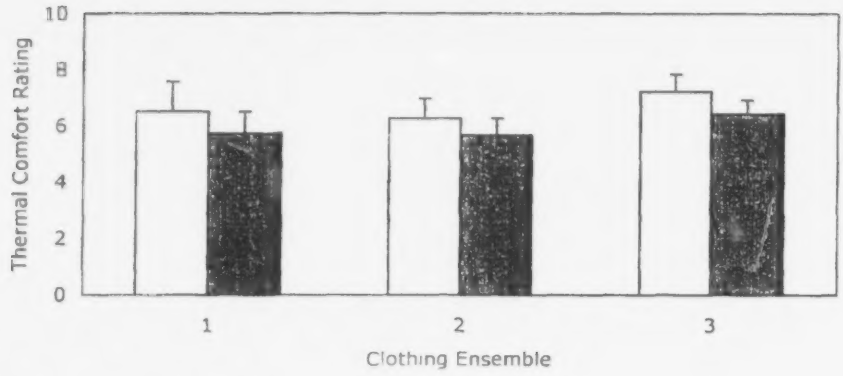

Figure 32: Whole body thermal comfort of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

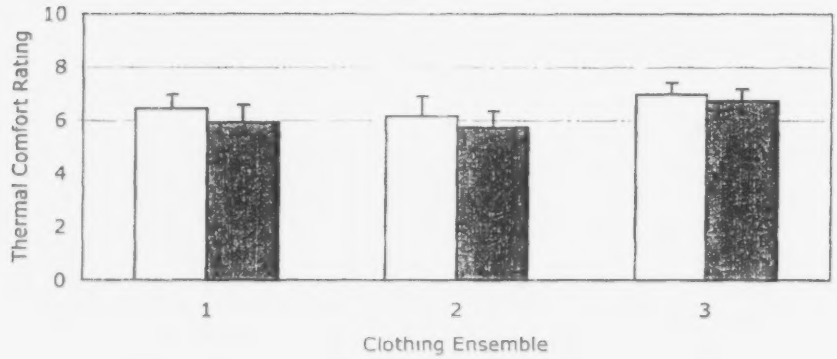

Figure 33: Whole body thermal comfort of Subject 1 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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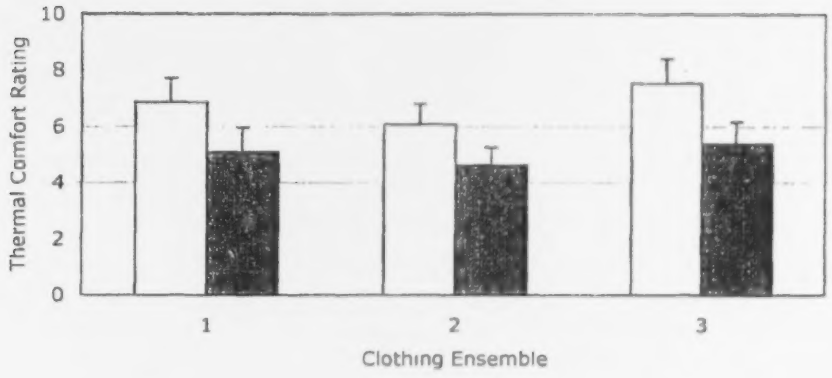

Figure 34: Whole body thermal comfort of Subject 2 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

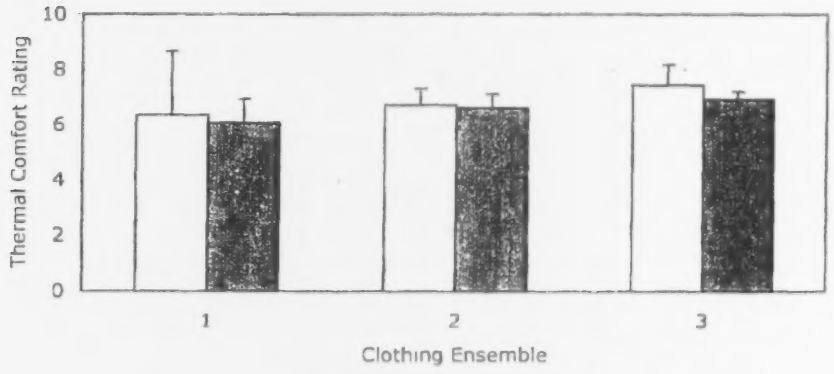

Figure 35: Whole body thermal comfort of Subject 3 during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

3.8 Perceived exertion

Perceived exertion data are presented in Figures 36 to 39.

Perceived exertion ratings were lowest for THREE. Perceived exertion ratings were lowest for Subject TW yet differed most for Subject JMR.

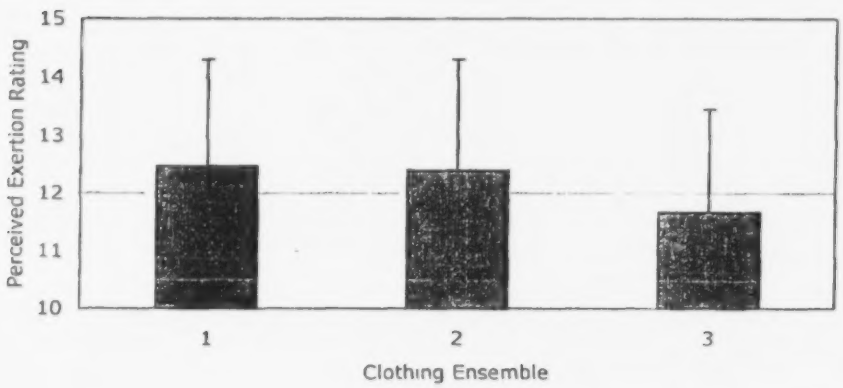

Figure 36: Ratings of perceived exertions of all subjects after skiing (grey) while wearing one of three clothing ensembles.

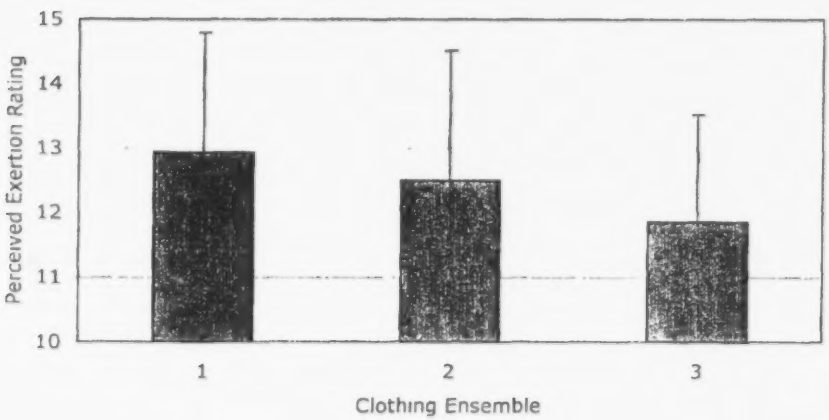

Figure 37: Ratings of perceived exertions of Subject 1 after skiing (grey) while wearing one of three clothing ensembles.

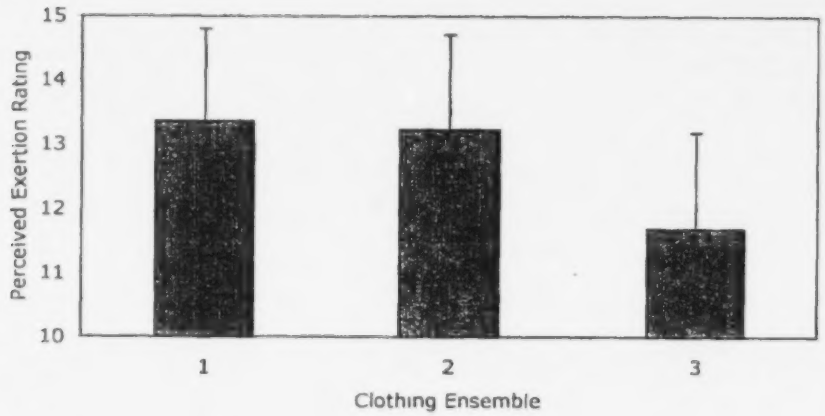

Figure 38: Ratings of perceived exertions of Subject 2 after skiing (grey) while wearing one of three clothing ensembles.

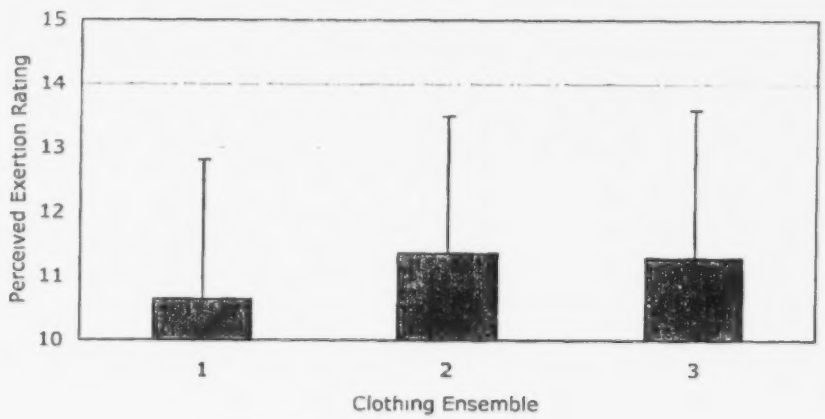

Figure 39: Ratings of perceived exertions of Subject 3 after skiing (grey) while wearing one of three clothing ensembles.

3.9 Humidity and water vapour pressure

Humidity and water vapour pressure data are presented in Figures 40 to 51.

Relative humidity values were similar. In general, relative humidity was highest for THREE. Inter-garment relative humidity was higher than skin-level relative humidity. Quadriceps relative humidity ranged greatly for ONE.

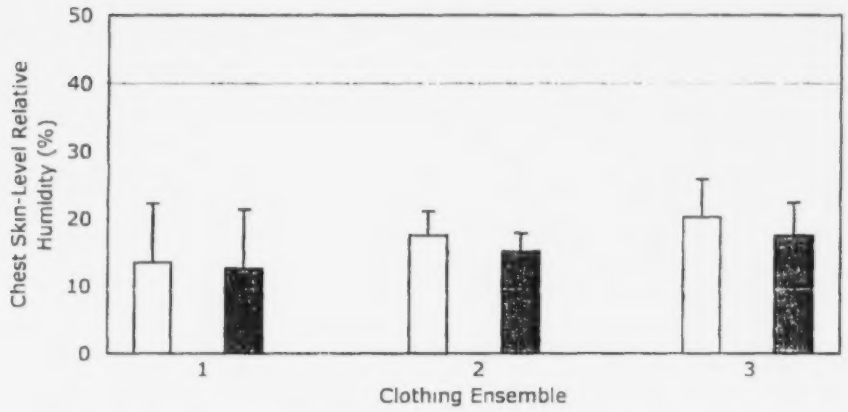

Figure 40: Mean chest relative humidity at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

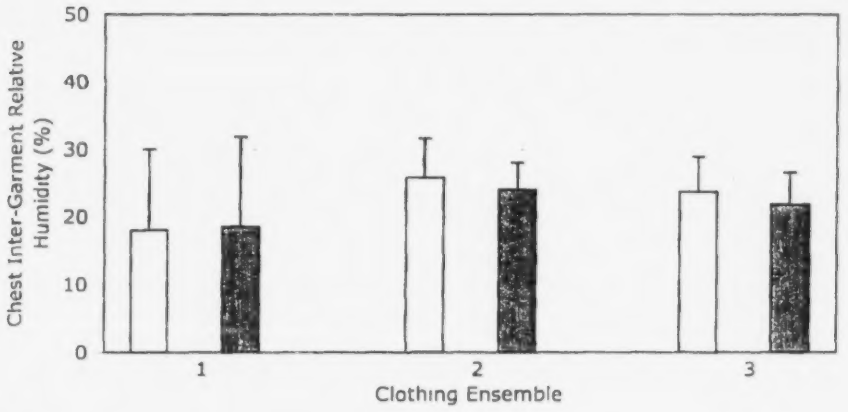

Figure 41: Mean chest relative humidity between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

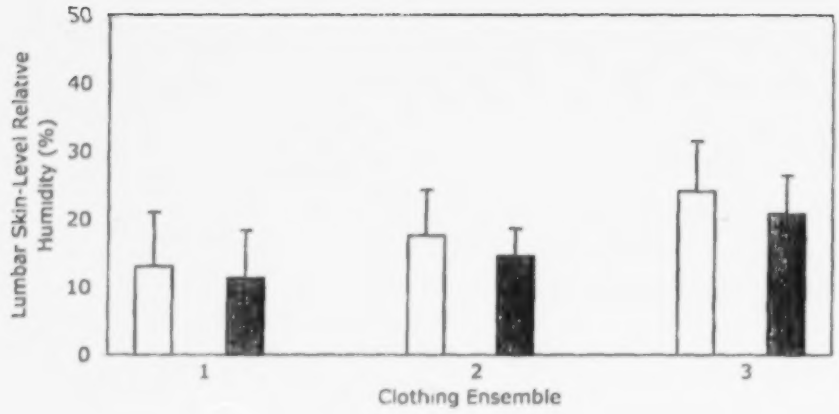

Figure 42: Mean lower back relative humidity at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

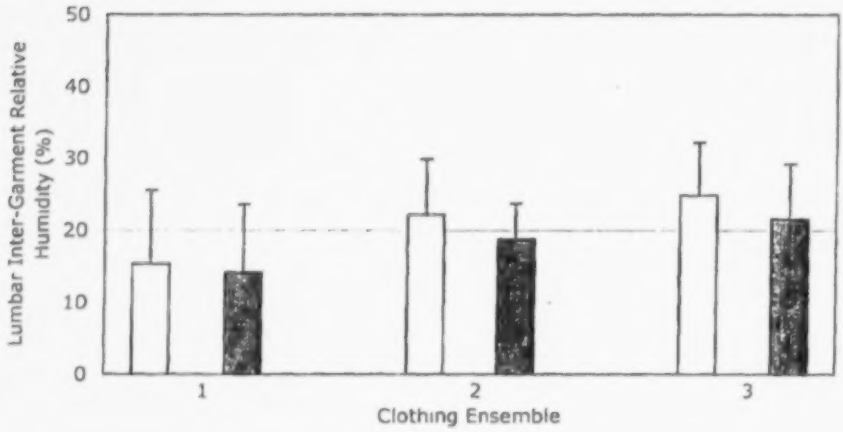

Figure 43: Mean lower back relative humidity between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

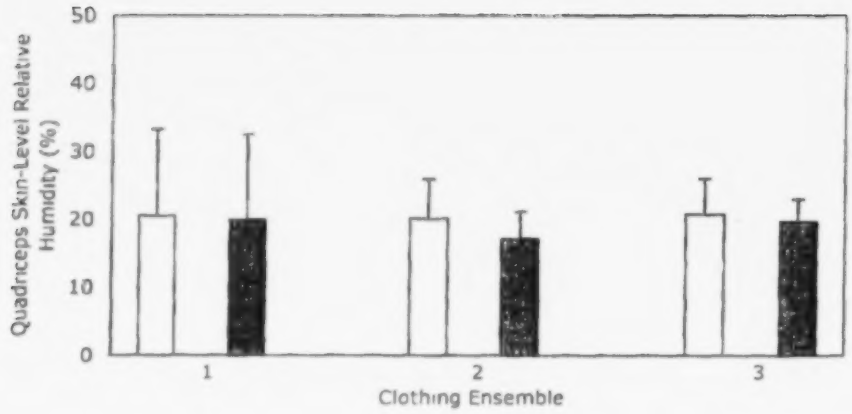

Figure 44: Mean thigh relative humidity at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

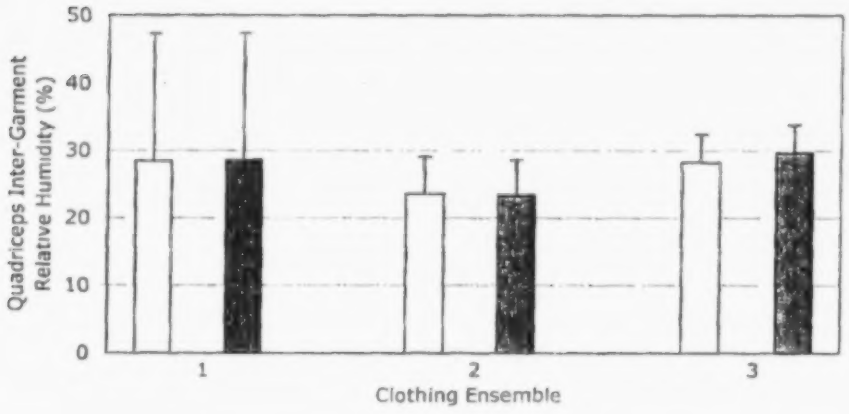

Figure 45: Mean thigh relative humidity between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

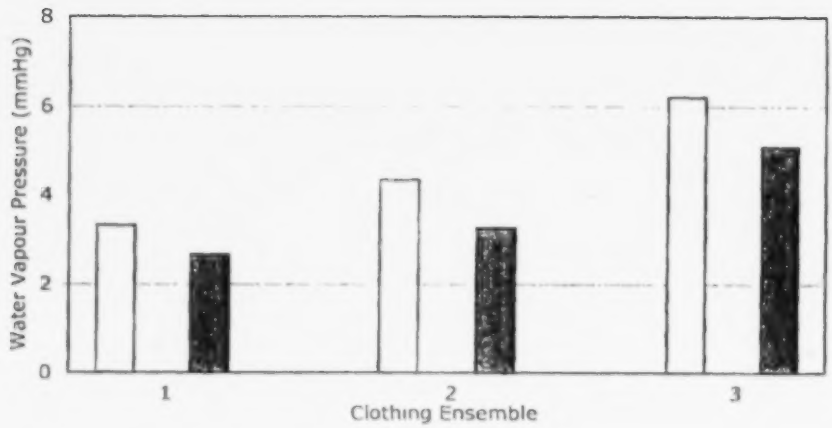

Figure 46: Mean chest water vapour pressure at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

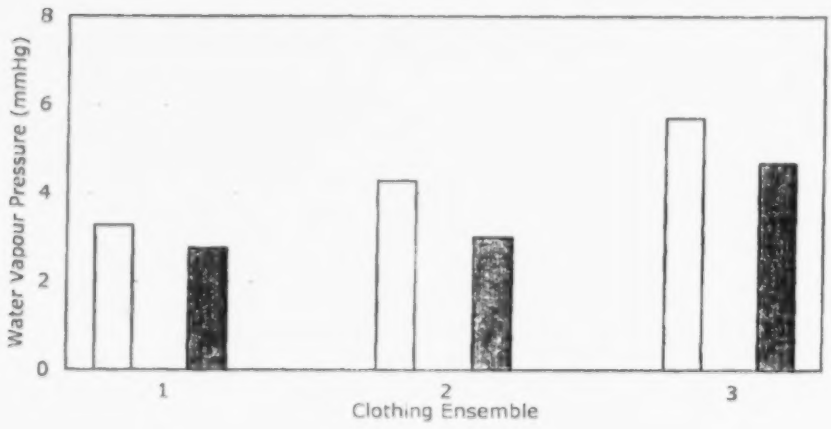

Figure 47: Mean chest water vapour pressure between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

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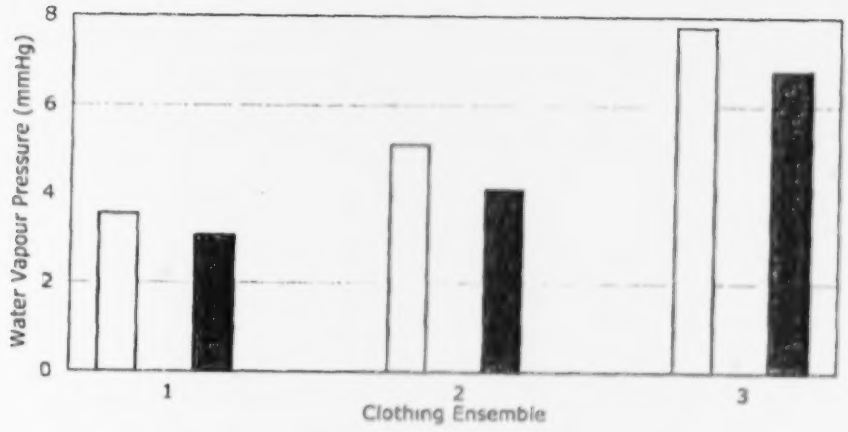

Figure 48: Mean lumbar water vapour pressure at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

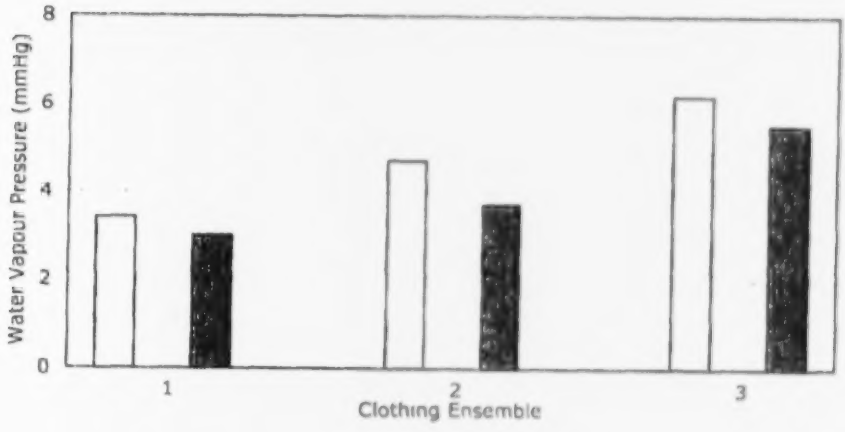

Figure 49: Mean lumbar water vapour pressure between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

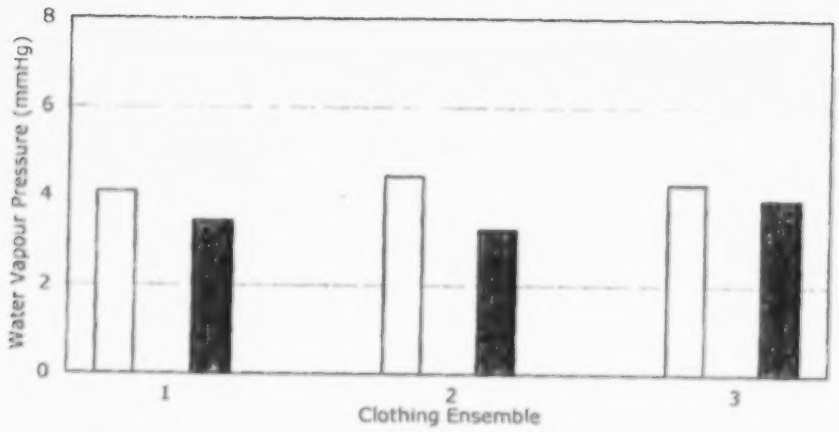

Figure 50: Mean thigh water vapour pressure at skin of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

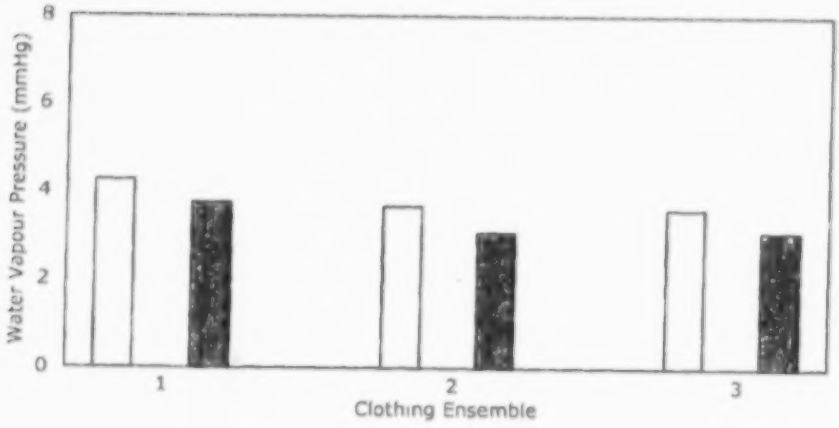

Figure 51: Mean thigh water vapour pressure between garments of all subjects during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

3.10 Sweat produced and evaporated

Sweat data are presented in Figures 52 to 54.

Sweat produced was lowest for TWO. Sweat held in garments was highest for TWO.

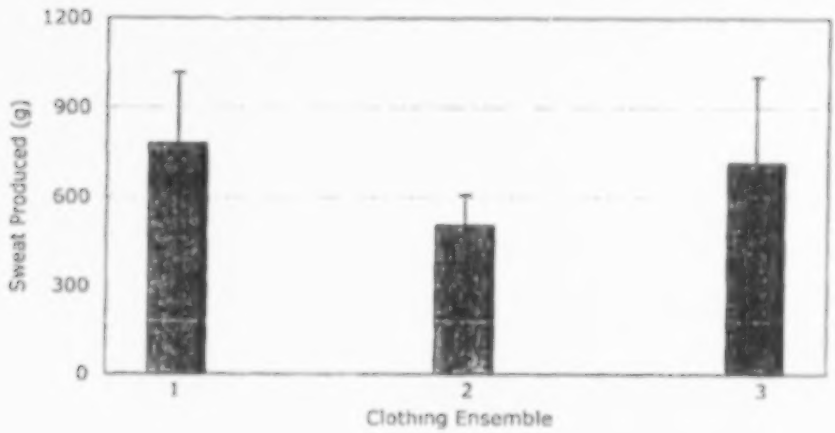

Figure 52: Mean sweat produced for all subjects while wearing one of three clothing ensembles.

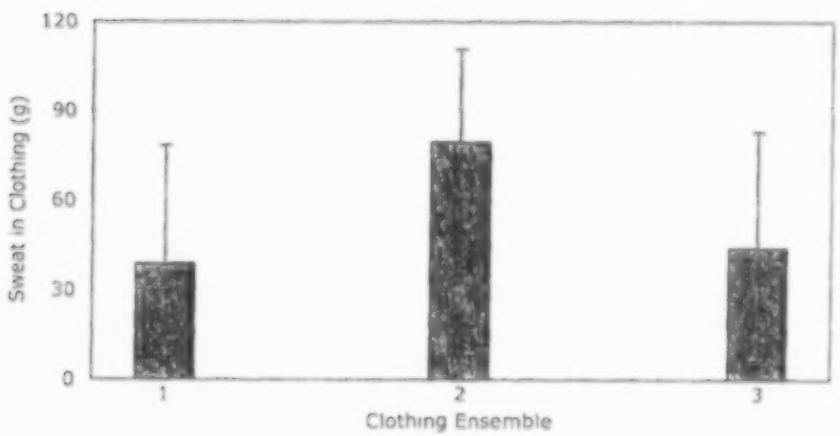

Figure 53: Mean sweat held in garments for all subjects while wearing one of three clothing ensembles.

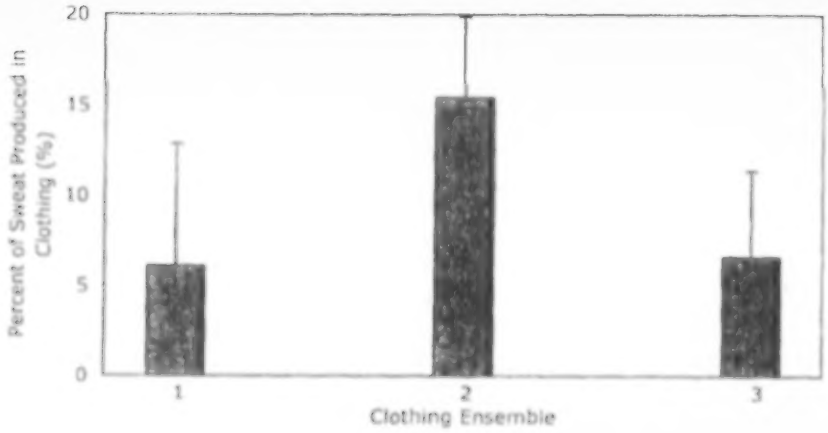

Figure 54: Mean percent of sweat produced that remained in garments for all subjects while wearing one of three clothing ensembles.

3.11 Clothing and system insulation

Clothing and system insulation data are presented in Figures 55 and 56.

Clothing and system insulation were greatest for THREE.

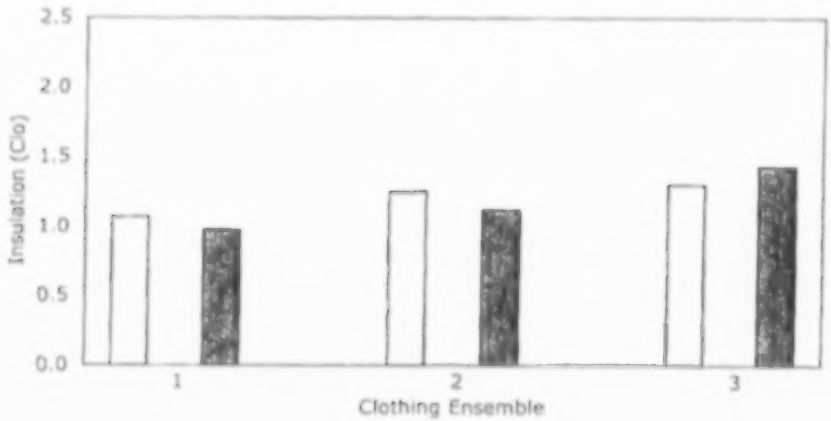

Figure 55. Average clothing insulation for all subjects while wearing one of three clothing ensembles.

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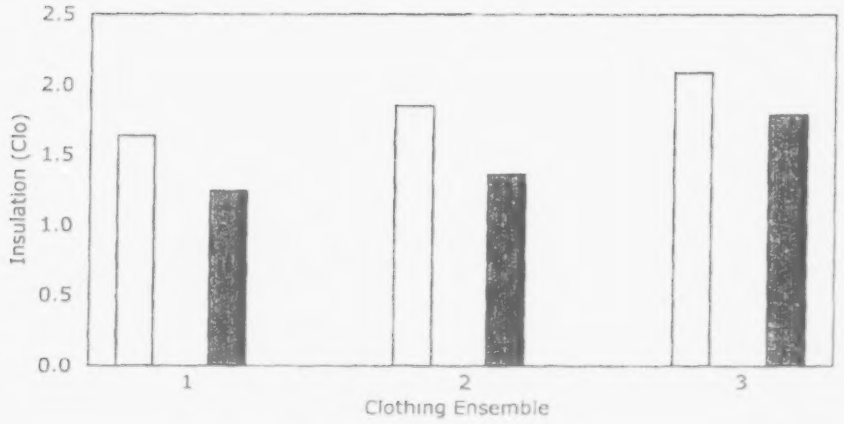

Figure 56: Average system insulation for all subjects while wearing one of three clothing ensembles.

3.12 Garment water vapour permeability

Garment water vapour permeability data are presented in Table 3.

Total water vapour permeability was highest for THREE.

Table 3: Garment water vapour permeability

Ensemble ONE	*R(m^2Pa s/kg)*	*millimetres of equivalent standard still air (ESSA)*	
X-Static top SM0177US	5.05E+07	1.4	
X-Static bottom SM0177US	5.05E+07	1.4	
2Ply nylon-lined Gore bottom SM01117US	5.91E+07	2.9	
3D mesh vented top: SM	6.25E+07	3.6	
Schoeller WB-400 top: SM01368	6.80E+07	4.6	
Total	29.06E+07	13.9 total	9.6 top/4 3 bottom
Ensemble TWO			
X-Static top SM0177US	5.05E+07	1.4	
X-Static bottom SM0177US	5.05E+07	1.4	
Schoeller WB-400 bottom: SM01233	6.80E+07	4.6	
Jonathon Fletcher fleece top	7.35E+07	5.6	
Schoeller WB-400 top: SM01352	6.80E+07	4.6	
Total	31.05E+07	17.6 total	11 6 top/6 0 bottom
Ensemble THREE			
X-Static top SM0177US	5.05E+07	1.4	
Kenyon Outlast bottom	5.21E+07	1.6	
3Ply Gore XCR bottom: SM01179US	5.52E+07	2.1	
Primaloft top: SM01644	1.17E+08	13.6	
3Ply Gore XCR top: SM0135US	5.52E+07	2.1	
Total	33.00E+07	20.8 total	17.1 top/3.7 bottom

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3.13 Environmental conditions

Environmental conditions data are presented in Figures 57 to 60.

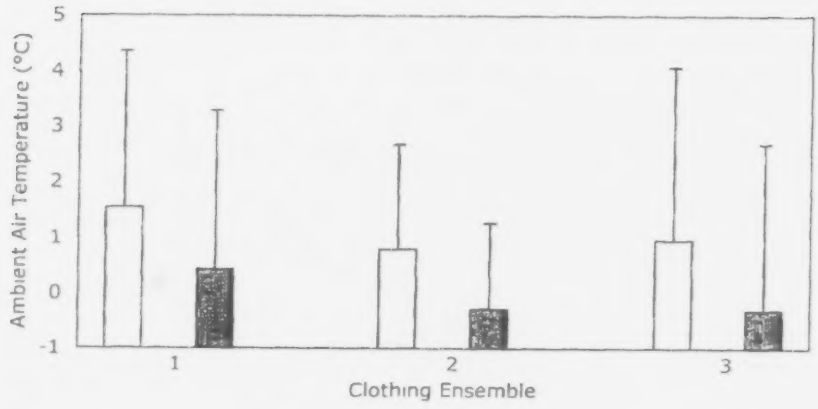

Figure 57: Ambient air temperature measured above subjects' shoulders during rest (white) or skiing (grey) while wearing one of three clothing ensembles.

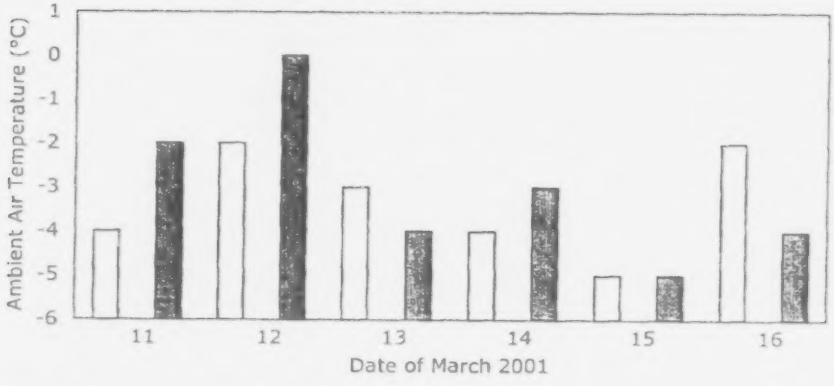

Figure 58: Ambient summit temperature at 08:00 (white) and 14:00 hours (grey) of each trial date.

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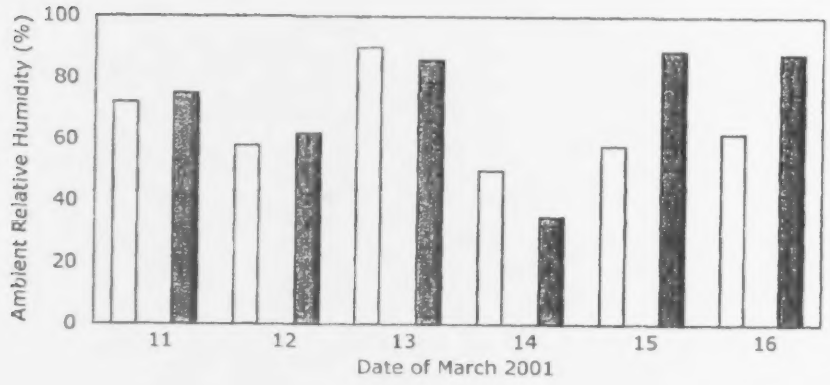

Figure 59: Ambient summit relative humidity at 08:00 (white) and 14:00 hours (grey) of each trial date.

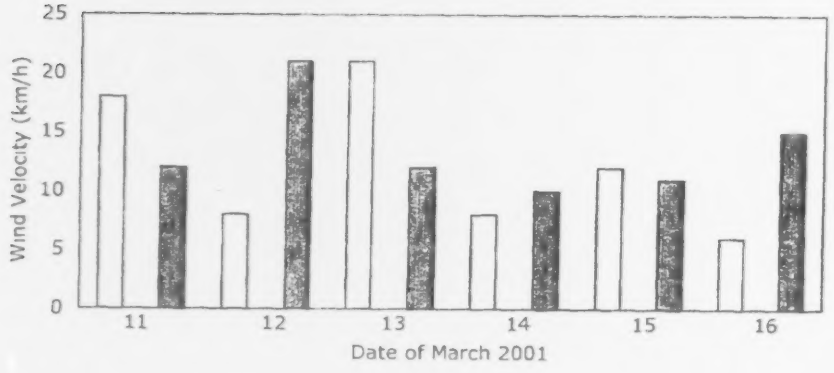

Figure 60: Ambient summit wind velocity at 08:00 (white) and 14:00 hours (grey) of each trial date.

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4. Discussion

The three clothing ensembles tested were designed to protect alpine skiers in air temperatures near or above freezing. Environmental conditions were a calm 1°C while activity levels averaged 3.7 times greater than rest. No ensemble provided effective comfort since all toe temperatures were 3 degrees below 15°C. Lower body garments provided less protection than the upper body as expressed by higher heat flux and lower skin temperature values.

Subjects perceived wind permeability as an important comfort factor. Subjects complained of wind permeability effects when ONE and TWO were worn. Subject 1 requested extra head, neck and feet insulation for the second exposure with TWO. Skiing activity and its resultant air flow increased heat flux for subjects anterior torso and legs as air compressed fabric layers and possibly passed into the clothing envelope. Air could enter through garment openings especially garment fabrics as noticed by higher heat flux ranges and lower skin temperatures for all upper and lower body sections covered with air permeable Schoeller WB-400. Low steady heat fluxes and high steady skin temperatures were recorded from upper back, lower back and arm as they were somewhat hidden from the air flows related to skiing. When activity changed from rest to skiing the areas that experienced greatest heat flux and skin temperature changes were hamstring, abdomen and chest.

Conversely, wind proofness may have contributed to desireable performance in all measurements. THREE evaluated best. THREE's windproof upper body insulation and outer shells maintained more constant and desirable skin temperature, heat flux, thermal comfort, perceived exertion, clothing insulation and system insulation without noticeable water vapour accumulation. Evaporative heat loss was greatest for THREE.

Sweat production and sweat accumulation were not problematic under these conditions with these ensembles. The amount of sweat produced was less than 100 grams/hour of which 50 grams is considered to be insensible (7). Only 6 to 15% of sweat produced was retained in any ensemble. Fabric characteristics may be more responsible for the retained sweat than the original amount of sweat produced. Quadriceps relative humidity ranged greatly for ONE which may the fabric's delay to transport water vapour across itself. Total water vapour permeability was worst for THREE but was not a problem in these conditions.

During rest, garment compression and increased conductivity was observed which caused subject's legs and back to lose a larger amount of heat to the previously weather-exposed chairlift seat. Greatest rest-to-ski changes for external suit temperature were from rear thigh.

Thermal comfort ratings were higher after skiing, which may emphasise the amount of activity required for comfort.

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The inability to analyse oxygen consumption in the field at the varied altitudes, temperatures and activities was unavoidable. Such metabolic equipment is beyond this study. An ingested pill or rectal core temperature should have been mandatory as such information could express whole body heat storage and rate of heat storage without compromising subject comfort. Salomon requested rectal core temperature be removed from the procedures. Undergarments with larger fit or greater stretch would have been desirable. Additional insulation could have increased sweat production thereby utilising all measured parameters to their potential.

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5. Conclusion

Clothing ensemble THREE was the most thermally comfortable for rest and skiing under the ambient condition tested. Windproof outer shell garments are preferable as the windproof layer was responsible for the preferred clothing ensemble THREE. Insulation for the lower body needs to be increased to ensure thermal comfort. Sweat accumulation was never a concern in this trial. If a clothing system had to be selected as is for comfort and protection in the condition tested, THREE would be favourable though not optimal.

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List of symbols

°C	degree Celsius
C	rate of convective heat loss
E	rate of evaporative heat loss from the skin
K	rate of conductive heat loss
R	rate of radiative heat loss
S	rate of body heat storage
VO_2	rate of oxygen uptake
W	watts
W/m^2	mean body heat loss

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Annex

Thermal comfort

1	so cold I am helpless
2	numb with cold
3	very cold
4	cold
5	uncomfortably cool
6	cool but fairly comfortable
7	comfortable
8	warm but fairly comfortable
9	uncomfortably warm
10	hot
11	very hot
12	almost as hot as I can handle
13	so hot I am sick and nauseated

Perceived exertion

6	very very light
7	
8	very light
9	
10	fairly light
11	

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12 somewhat hard

13

14 hard

15

16 very hard

17

18 very very hard

19

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4 AUTHORS

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14. ABSTRACT

(U) DCIEM field-tested three prototype ski clothing ensembles for thermal and vapour transfer characteristics. Each ensemble differed in their combinations of insulation and shell fabrics, which would affect their capacity to retain heat and transfer water vapour to the environment. Three male subjects were used to test three conditions. Each condition required a chairlift ascent before skiing in sequence each of 14 pre-set, intermediate to expert descents at a western Canadian ski resort. Subjects experienced 268.0 minutes (+/-7.0 minutes) exposure of which 85.3 minutes (+/-4.7 minutes) were active skiing. Subjects' activity levels averaged 3.7 times greater than rest. No ensemble provided effective comfort since all toe temperatures were 3 degrees below 15°C. Lower body garments provided less protection than the upper body. Subjects perceived wind permeability as an important comfort factor. During rest, garment compression and increased conductivity was observed which caused subject's legs and back to lose a larger amount of heat to the previously weather-exposed chairlift seat. When activity changed from rest to skiing the areas that experienced greatest heat flux and skin temperature changes were hamstring, abdomen and chest. Skiing activity and its resultant air flow increased heat flux for subjects anterior torso and legs. Sweat accumulation was never a concern in this trial. The clothing ensemble with windproof upper body insulation and outer shells maintained more constant and desirable skin temperature, heat flux, thermal comfort, perceived exertion, clothing insulation and system insulation without noticeable water vapour accumulation.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) thermal insulation; vapor transfer; vapor resistance; sweating; skin temperature; heat loss; thermal comfort